Reply to the comment on " Manipulating the frequency-entangled states by an acoustic-optical modulator"

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Abstract

In the paper [1], authors claim that the scheme for entanglement swapping using an acoustic-optical modulator [2] is flaw. In this reply, we show there is a trivial mistake in the scheme [2], but the main conclusion is still correct, that is, the acoustic-optical modulator can be used to manipulate the frequency-entangled state.

In the paper [1], Resch et.al show that the transformation done by acoustic-optical modulator (AOM) should be

$$\left|\omega\right\rangle_1 \overset{AOM}{\rightarrow} \frac{1}{\sqrt{2}}[\left|\omega\right\rangle_t - i\left|\omega+\delta\right\rangle_d]$$

$$\left|\omega+\delta\right\rangle_{1'} \overset{AOM}{\rightarrow} \frac{1}{\sqrt{2}}[\left|\omega\right\rangle_t + i\left|\omega+\delta\right\rangle_d], \tag{1}$$

(where $t, d, 1, 1'$ refer to the special mode labels shown in Fig 1 of the Ref. [1], $\omega, \omega+\delta$ are photon frequencies), not be

$$\left|\omega\right\rangle_1 \overset{AOM}{\rightarrow} \frac{1}{\sqrt{2}}[\left|\omega\right\rangle_t + \left|\omega+\delta\right\rangle_d]$$

$$\left|\omega+\delta\right\rangle_{1'} \overset{AOM}{\rightarrow} \frac{1}{\sqrt{2}}[\left|\omega\right\rangle_t + \left|\omega+\delta\right\rangle_d]. \tag{2}$$

This is true. We make a trivial mistake in this transformation, and we thank them very much for pointing out this mistake. But this small mistake does not change our conclusion,

that is, AOM can be used to manipulate the frequency-entangled state. Next, we show it in detail.

In the Ref. [1], authors claim that no entanglement swapping has occurred between photons 1 and 4, according to Eq. (12) of the Ref.[1], which is derived from the proper transformation of Eq. (1) done by AOM. But Eq.[12] can be rewritten as the following

$$
\begin{aligned}
& |\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}(|\omega\rangle_{T_2}-i|\omega+\delta\rangle_{T_2'})(|\omega\rangle_{T_{1'}}-i|\omega+\delta\rangle_{T_1'})+\\
& |\omega\rangle_{1}|\omega\rangle_{4'}(|\omega\rangle_{T_{1'}}+i|\omega+\delta\rangle_{T_1})(|\omega\rangle_{T_2}+i|\omega+\delta\rangle_{T_2'})\\
={}& \{[|\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}+|\omega\rangle_{1}|\omega\rangle_{4'}]|\omega\rangle_{T_{1'}}|\omega\rangle_{T_2}-\\
& [|\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}+|\omega\rangle_{1}|\omega\rangle_{4'}]|\omega+\delta\rangle_{T_1}|\omega+\delta\rangle_{T_{2'}}-\\
& i[|\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}-|\omega\rangle_{1}|\omega\rangle_{4'}]|\omega+\delta\rangle_{T_1}|\omega\rangle_{T_2}-\\
& i[|\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}-|\omega\rangle_{1}|\omega\rangle_{4'}]|\omega\rangle_{T_{1'}}|\omega+\delta\rangle_{T_{2'}}]\}
\end{aligned}
\tag{3}
$$

From the equation above, if one photon enters AOM1 and at the same time another photon enters AOM2 (refer to the Fig. 2 of the Ref. [1]), when one of two detectors in modes T_1 or $\mathrm{T}_{1'}$ and one of the other two detectors in modes T_2 or $\mathrm{T}_{2'}$ fire simultaneously, photons 1 and 4 will be projected into a maximally frequency-entangled state. The only difference between equation above and the Eq.(10) of the Ref. [2] is a maximally entangled state $|\omega+\delta\rangle_{1'}|\omega+\delta\rangle_{4}-|\omega\rangle_{1}|\omega\rangle_{4'}$ can be obtained with 50% probability, which is not included in Eq.(10) of the Ref.[2] because of improper transformation. So the main idea of our scheme is correct, although it needs a small revision.

Similarly, AOM can also be used to create a Greenberger-Horne-Zeilinger (GHZ) state. Comparing to Eq.(16) of the Ref.[2], the correct equation should be (omit the constant factor)

$$
\begin{aligned}
& [|\omega\rangle_{1}|\omega+\delta\rangle_{3'}|\omega\rangle_{4'}+|\omega+\delta\rangle_{1'}|\omega\rangle_{2'}|\omega\rangle_{4}]|\omega\rangle_{T}+\\
& i[|\omega\rangle_{1}|\omega+\delta\rangle_{3'}|\omega\rangle_{4'}-|\omega+\delta\rangle_{1'}|\omega\rangle_{2'}|\omega\rangle_{4}]|\omega+\delta\rangle_{T'}\,.
\end{aligned}
\tag{4}
$$

Obviously, when one of detectors in modes T or T' fires, Eq. (4) will be projected into a GHZ

state. The only difference is that two GHZ states $\left|\omega\right\rangle_1 \left|\omega+\delta\right\rangle_{3'} \left|\omega\right\rangle_{4'} \pm \left|\omega+\delta\right\rangle_{1'} \left|\omega\right\rangle_{2'} \left|\omega+\delta\right\rangle_4$ can be created with 50% probability respectively.

In conclusion. in spite of a small mistake we make, the main result of our paper is correct, that is, AOM can be used to manipulate the frequency-entangled state.

REFERENCES

[1] K. J. Resch, S. H. Myrskog and A. M. Steinberg, arxiv:quant-ph/0011031

[2] B. S. Shi, J. Y. Jiang and G. C. Guo, Phys. Rev. A., 61, 064102 (2000)